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EXPOSURE SYSTEM FOR ANIMAL STUDIES INVOLVING HIGH-LEVEL 60-Hz MAGNETIC FIELDS

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The design of an animal exposure chamber used in the Ontario Hydro MFRRS study has been reviewed and modified for use in studies requiring an exposure to high-strength 60-Hz magnetic fields. New design criteria and specifications are described in this report.

INTRODUCTION

An animal study has been proposed, as part of the Ontario Hydro EMF Risk Assessment Program (EMFRAP), to test the hypothesis that an association may exist between exposure to 60-Hz magnetic fields and the incidence of some types of cancer. According to the present protocol for this study, animal exposure chambers will be required with the capability to accommodate six different groups of laboratory mice, each containing up to 96 animals, and to expose four of these groups to preselected magnetic field levels up to 2 mT rms.

This requirement can be met by using 12 exposure chambers similar to the ones used for the Magnetic-Field Rodent Reproductive Study (MFRRS)/1/. However, modifications to the design of the electrical parts of the chamber will be required to adapt the design for operation at high levels of 60-Hz fields. Some of the necessary adaptations have been discussed in the earlier report.

This report describes further work that has been done to finalize the electrical design and to prepare guidelines for the procurement of animal exposure chambers based on the MFRRS apparatus concept.

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GENERAL DESIGN REQUIREMENTS

The exposure chamber used in the MFRRS experiment consisted of three parts. One part was an animal cage assembly that was designed to hold 48 mice in 8 individual cages. Each cage was provided with food and water *ad libitum* and complied with the space requirements of the Canadian Council on Animal Care. Interlocking with the cage assembly, but not in physical contact with it, was a free-standing magnetic-field generating coil. The third part was a coil driver circuit capable of producing 20-kHz magnetic field waveforms with levels up to 0.2 mT peak-to-peak.

For the 60-Hz study, the cage assembly design may be used without change. There may be some cost advantage, however, in replacing custom-made glass and plastic components, such as cage lids, feeders, and sipper tubes, with commercially available ones or more durable metal ones if this can be done without introducing adverse effects. The cages themselves, and the cage support structure, must be custom made. The construction is fairly straightforward, however, and they may be obtained without too much difficulty from local fabricators.

New 60-Hz driver circuits, preferably operating directly from a standard 115-V, 15-A wall outlet, are required. The drivers must be compatible both with the physical layout of the animal laboratory, and with the quality assurance and security systems provided for the study, details of which are not presently available. Nevertheless, an examination of the basic requirements shows that they are not very demanding and it is proposed to meet them with an in-house design when full details are available.

New coils also are required, because the 2 mT field level specification exceeds the capability of the original design. A substantial fabrication effort will be required to produce twelve coils having the desired performance characteristics. This effort is considered to exceed the capabilities of the Research Division at the present time, in consequence of which, detailed specifications for the production of the coils by an outside supplier have been prepared.

SUBSTITUTION OF CAGE COMPONENTS

Although the magnetic fields specified for the present study are stronger than the MFRRS fields, the rate of change of field is more than 50 times lower. Induced currents in metal components will be correspondingly reduced. Several tests were performed in a 60-Hz field of 2 mT to determine what metal parts, if any, could be used with the cages.

First, a commercially-available wire cage cover was tested. The cover was considered not acceptable due to excessive vibration. Subsequent tests showed that the cover was made from ferrous metal.

Second, a loop of AWG No 12 copper wire with a diameter of 25 cm (about the size of a single cage) was tested. The circulating current with the loop aligned for maximum induction was about 9 A, but there was no perceptible vibration. The perturbing effect of such a circulating current on the ambient field is readily estimated in terms of the ratio of the perturbing field B' to the ambient field B.

At the center of any loop, the ratio at 60 Hz is

$$\frac{B'}{B} = \frac{\mu_o \omega}{4r} = 1.18 \times 10^{-4}/r$$

where r is the resistance of the wire per unit length. As an example, the loop-center perturbation is about 2% for an AWG #12 copper wire loop of any diameter. Conversely, the perturbing field close to the wire can be very much larger (10% at 1 cm from conductor of the 25-cm diameter copper loop) but decreases with decreasing diameter.

The perturbing fields for type 304 stainless steel will be about 40 times lower than those for copper at 60 Hz.

Finally, a commercially available stainless steel feeder was tested. The feeder was determined to be non-magnetic and displayed no perceptible vibration. Vibration levels measured in a cage with a model B&K 2635 accelerometer unit were found to be less than the background signal levels of about 0.006 m/s^2.

These tests show that it should be safe to use small non-magnetic stainless steel fittings and components in the plastic cages. Stainless steel cage covers, if available in suitable sizes, may also be satisfactory but in case of doubt can be avoided without penalty due to the availability of a low-cost alternative.

FIELD GENERATING COILS

The principal design criteria for the field generating coils are as follows:

1. The coils must produce a magnetic field of the required field strength and with the specified spatial distribution both inside and outside of the exposure chamber.

2. The coils should be well matched to the line voltage so that they do not require large power transformers and heavy bus conductors.

3. The need for water cooling should, if possible, be avoided.

4. The construction should employ good design practices to minimize the production of noise and vibration.

Preliminary specifications for a coil meeting these criteria were developed in a previous report/1/. The specifications have been refined further by adopting a modular winding method of construction (each coil to consist of 12 modules), and building and testing two modules in the laboratory. The same winding modules were used to generate the 2 mT magnetic fields for the tests described in the preceding section.

The modules were made from 18 turns of 3/4" by 0.040" copper tape and demonstrated the feasibility of obtaining a high winding density by the use of flat conductors. This construction is also thought to be less susceptible to interwinding vibrations than windings that use round conductors, and indeed no interwinding vibrations could be felt at full rated current through the windings.

Intrawinding vibrations were detectable, and were tested by making accelerometer measurements with the two modules placed side-by-side. Initial levels of 0.4 m/s^2 were reduced to 0.02 m/s^2 when the two modules were firmly clamped together.

Each module generates about 8 watts of heat at full current. In continuous operation, the conductors become slightly warm to the touch.

Based on previous calculations and the results of these tests, draft tendering specifications for the supply of twelve assembled coils have been prepared. These are listed the Appendix.

COIL DRIVER CIRCUITS

Although it is in principle a simple matter to provide each coil with the necessary 60-Hz current, several factors must be considered in the design of the supplies. These include;

- the need for identical visual treatment of all coils to maintain "blindness";
- the distance between the supplies and the coils, and the required current capacity of the connecting wires;
- the need for regulation and control of the quality of the supply current;
- the significance of current or voltage transients produced when the supplies are switched on or off.
- The configuration and interconnections needed to "interface" with monitoring, control, and security systems as appropriate for the physical layout of the apparatus.
- The need for and availability of back-up supplies.

Provision of a final design will depend on the release of information about the physical layout of the apparatus, the flexibility of operation and the degree of automation that is required, and the details of the monitoring, control, and security systems. For the present, a simple conceptual design is proposed and some test have been carried out to verify the suitability of the concept.

The proposed design, shown in Figure 1, places all drivers in a single location with a "blind" connection box to which the individual coils are connected. The coils themselves are paired, two coils being connected to each driver and operated as a single unit for monitoring and control purposes. The monitoring and control functions are relegated to a separate computer system whose function would be to monitor the analog status signals and to turn individual pairs of coils on or off in accordance with a prescribed protocol. Any changes in field assignments among the twelve coils would be made by manually reconnecting jumpers in the connection box.

Tests performed in the laboratory focussed on the control of the current through inductive loads under steady state and transient conditions when the loads are supplied through a Sola constant-voltage, harmonic-neutralized, regulating transformer type CVH-1. Because power-factor correction is proposed to reduce the VA requirements of the high-field supply, tests were done with and without power-factor correction of the load.

Steady-state tests showed that the harmonic content of the current supplied to a power-factor corrected load was very high. However, the harmonic content of the current through the coil itself was low (THD < 1%). Line voltage regulation with power-factor correction (phase angle 9°) was 10:1. The constant-voltage transformer was observed to produce considerable heat and noise under steady-state operation.

Switching tests showed variable transient performance depending on the location of the switch (line side or load side of the constant-voltage transformer). Switching off from the line side produces a decay of 5 to 10 cycles during which the frequency drops to 0. Switching on from the load side produces a current offset up to 100% that decays in about 5 cycles. Switching off from the load side produces a smooth drop in current but also produces a voltage transient up to 3 or 4 times the operating voltage if a power-factor correction capacitor is not used.

These tests show that the proposed system should provide acceptable performance provided that simple precautions, such as locating the constant-voltage transformer in a separate room and installing surge suppressors on the coils, are taken, and that transient field excursions of a few cycles duration are tolerable. If any of the characteristics of the system are unsatisfactory, then appropriate design changes will have to be made.

CONCLUSIONS

Changes are proposed in the design of the animal exposure chambers used in the MFRRS experiment to make the chambers suitable for a forthcoming study involving high-strength 60-Hz magnetic fields. Some of the design changes have been evaluated in a series of laboratory tests. It is proposed to obtain the various parts of the chambers from outside suppliers where possible, but to assemble and test the coil driver circuits in house. Specifications have been prepared to the extent possible on the basis of available information.

Approved:

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1. Magnetic Field Rodent Reproductive Study (MFRRS) Exposure System. Research Report 88-125-K.

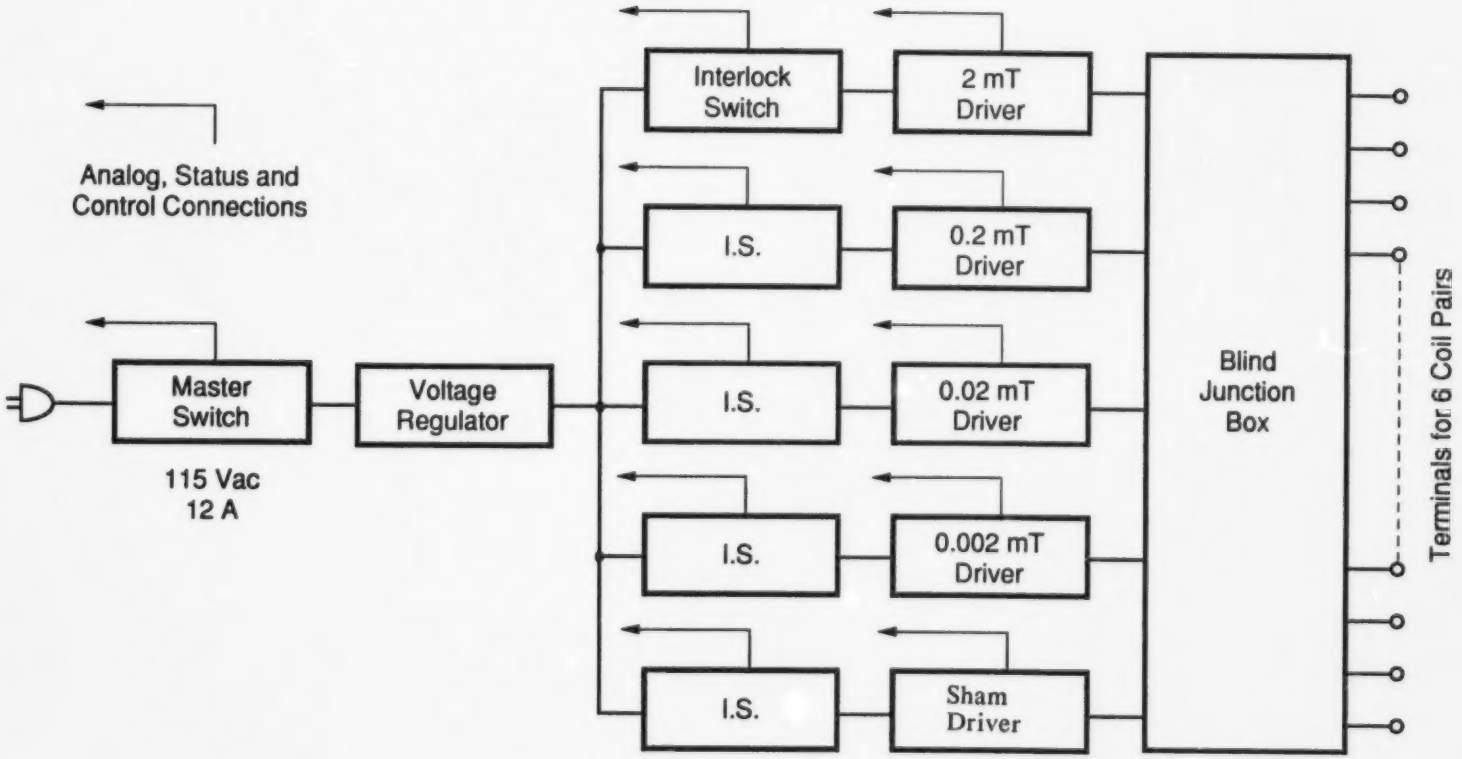

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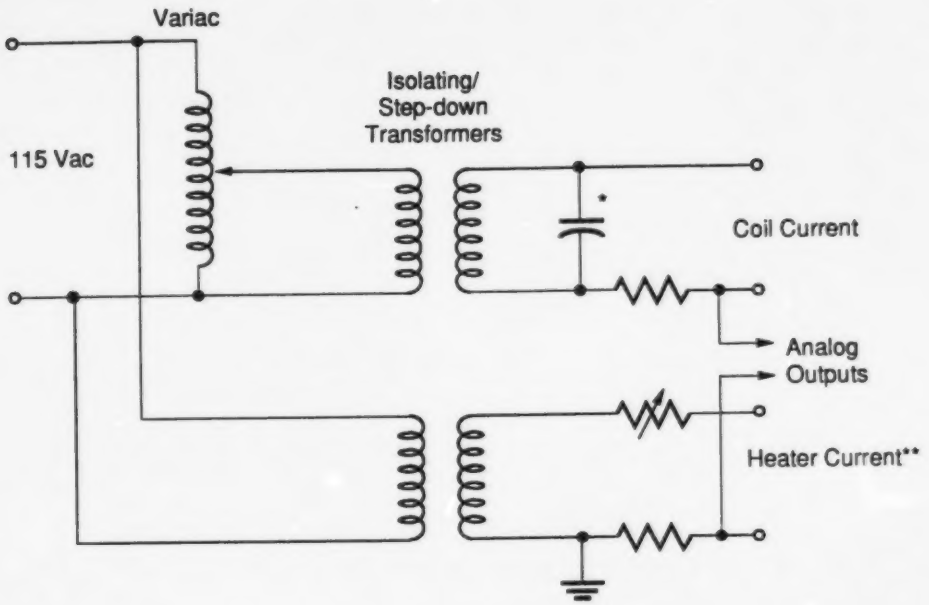
FIGURE 1 (a)

SCHEMATIC OF PROPOSED COIL DRIVER SYSTEM



* Power-factor correcting capacitor (2 mT)
** Not required on 2 mT driver

FIGURE 1 (b)

SCHEMATIC OF CONCEPTUAL COIL DRIVER

APPENDIX

TENDERING SPECIFICATIONS
FREE STANDING AIR-CORED INDUCTORS

Twelve custom-designed air-cored inductors (coils), each measuring about 35 x 35 x 23 inches, are required. The coils are to be of a modified helmholtz-coil type each containing six "figure-of-eight" double-loop windings connected in series and mounted on a lightweight rigid frame. An example of a coil designed to similar geometrical specifications is shown in Figure A1.

The method proposed for constructing the coils is a modular one, in which each coil is assembled from a number of identical simple rectangular windings, with an open framework engineered to provide adequate strength and resistance to vibration.

DETAILED COIL SPECIFICATIONS

1. Winding Details

   Each coil is to be assembled from 12 identical rectangular windings. Each winding is to contain 20 turns of wire with a total resistance of not greater than 0.05 ohms. The maximum current through each winding will be about 14 A (rms) and the maximum voltage across the coil will be about 140 V (rms) at 60 Hz. The dimensional limits of each winding are not to exceed those shown in Figure A2.

   NOTE: Winding and frame dimensional limits are adequate to accommodate construction consisting of 20 turns of AWG No 4 or 5 low-resistivity copper wire or equivalent, on an aluminum channel frame. In addition, some dimensional latitude is provided to allow for other constructions, which may be preferable because of engineering or cost advantages. It is not necessary that the actual dimensions coincide with the dimensional limits shown.

2. Winding Frame Details

   Each winding is to be supported on a solid frame made from non-magnetic material with dimensions not to exceed the limits shown in Figure A3. If metal frames are used, a "broken" joint shall be incorporated in the frame so that no metallic loop is formed through which current can flow. A broken joint here is considered to be one with adequate structural strength but no metal-to-metal contact.

   NOTE: The winding frames may have framing attachments or fittings that extend beyond the dimensional limits shown. However, it is important that these comply with the location restrictions of Item 5.

3. Electrostatic Shielding of Winding

   Each winding is to have electrostatic shielding (ie a metal layer) covering at least the front, back, and inside surface of the winding. The shielding may be made of copper foil or may be supplied by a metal frame. In either case, the shielding shall not form a closed loop either axially or radially. Provision shall be made for grounding the shielding to an external connection.

4. Heating of Winding

Each winding shall have a resistive heating wire embedded in the winding with a heat generating capacity of not less than 10 watts. The wire shall be installed around the circumference and returned by the same path so that it will not form a closed loop.

5. Assembly of Coil

Twelve windings are to be assembled with non-magnetic attachments and spacers to form a complete coil having dimensions within the limits shown in Figures A4(a) and A4(b). An open structure with minimal obstruction of light and air circulation is required. If metal parts are used, "broken" joints shall be incorporated so that no metallic loops are formed.

NOTE: It is important that framing members and attachments do no intrude on a specified interior space within the finished coil as shown in Figure A4(a). Effectively, this allows fittings to intrude beyond the minimum frame dimensions by up to 1 inch at selected locations.

6. Electrical Connection of Windings

The twelve windings shall be connected in series as shown in Figure A5 with copper conductors having the same cross-section as the winding conductor. The twelve heating wires shall also be connected in series or in series-parallel for a total resistance between 50 and 100 ohms, and the shield grounds shall be connected together at a common grounding terminal. All connections shall be brought neatly to a central location on one side of the coil. Live terminals shall be designed to avoid electrical shock hazard.

7. Coil Support Structure

The fully assembled coil shall be supplied with a non-magnetic, non-current carrying support structure with height-adjusting screws at each corner as shown in Figure A6. The height of the center of the coil when mounted on the support structure shall be adjustable from 37 to 38 inches above the floor.

8. Sound and Vibration

The overall design of the coil shall be such that vibration and sound levels are tightly controlled through appropriate engineering principles. Accelerometer readings will be taken on the coil frame at maximum current and should not exceed 0.02 m/s^2.

9. Mechanical Properties

The coil assembly shall be designed for lifting by manual fork-lift or crane transporting devices.

TENDERING PROCEDURE

Bids should contain a description of the technical design solutions proposed. To provide quality assurance, a prototype unit is to be built and delivered to the Ontario Hydro Research Division for testing and evaluation. On successful completion of the tests, authorization will be given to manufacture and deliver the remaining units.

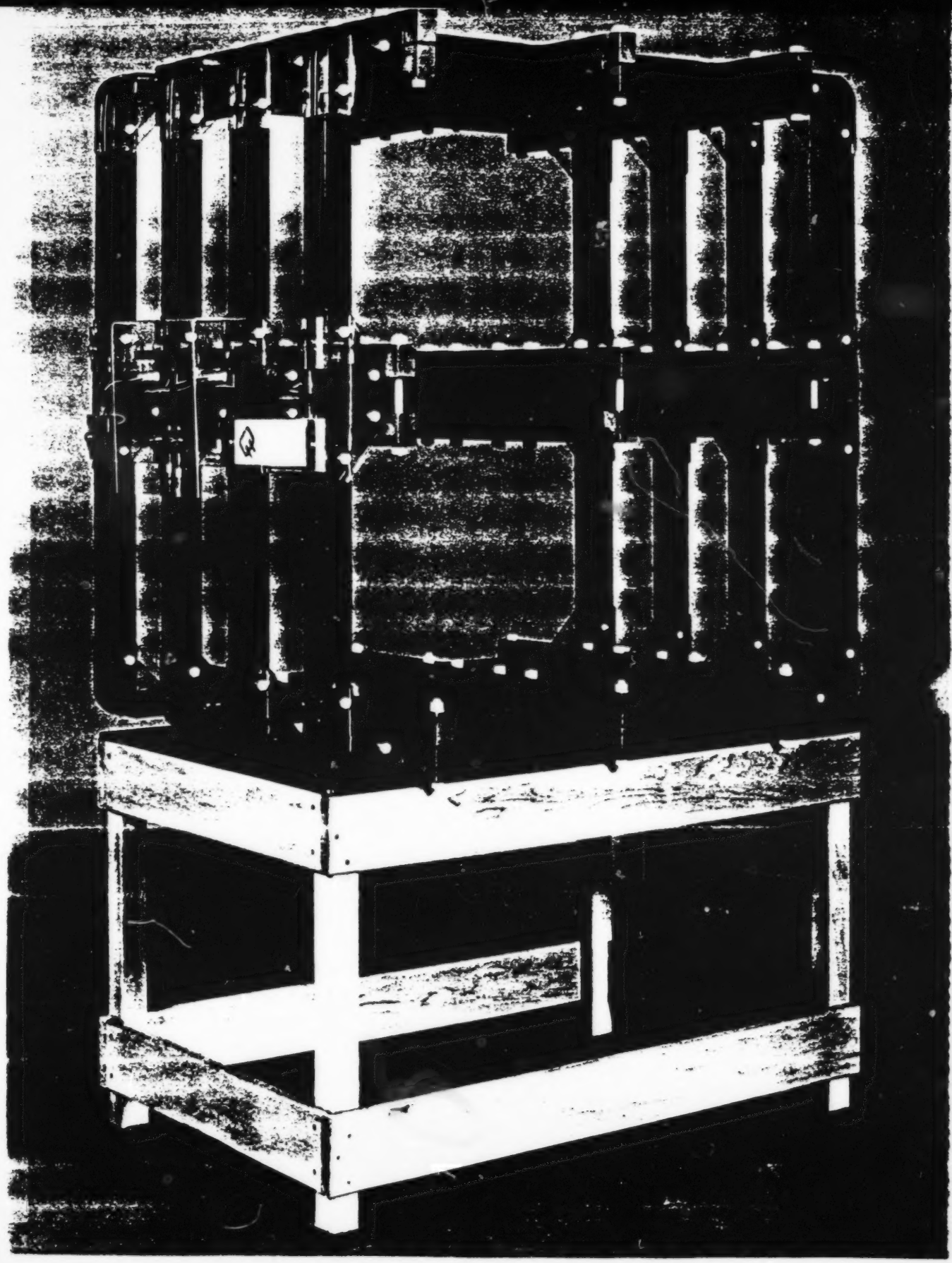
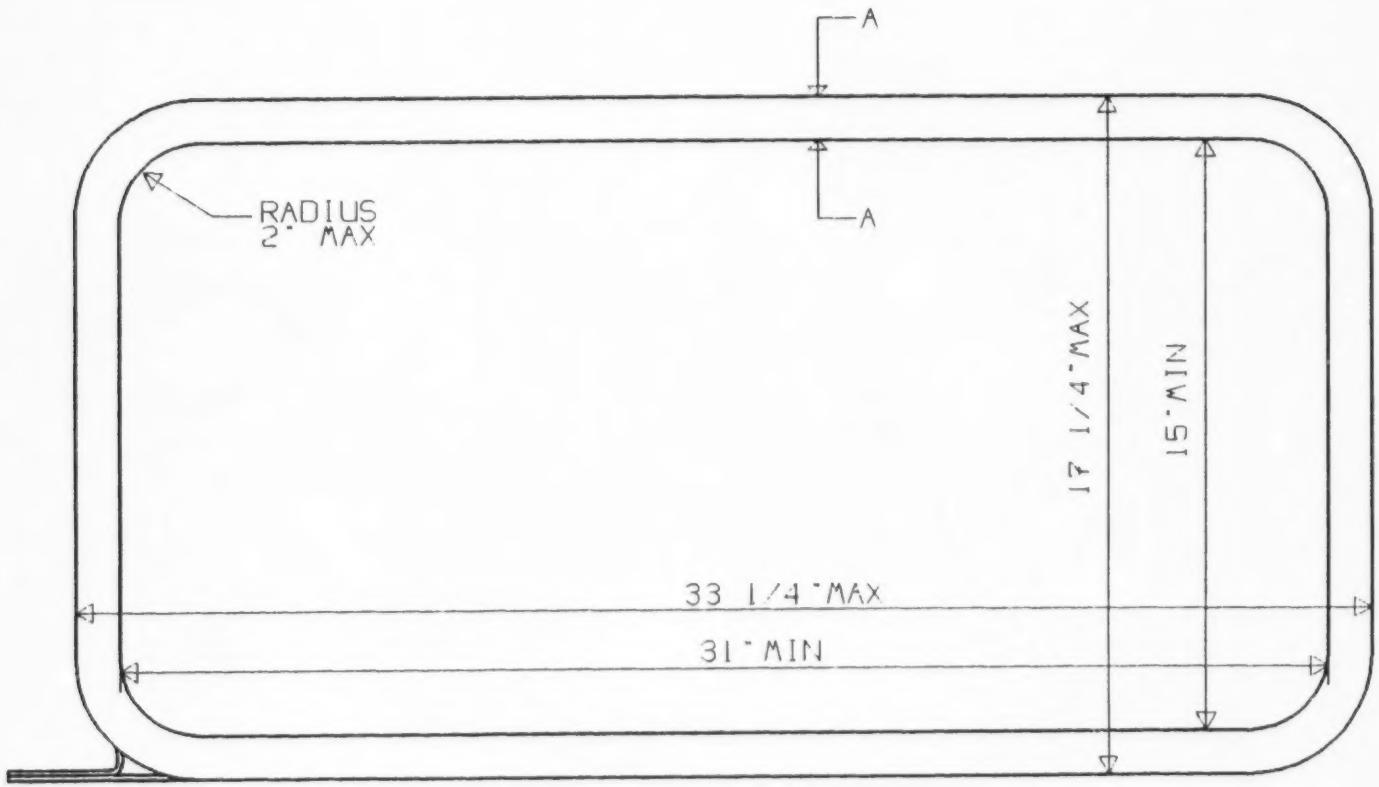


FIGURE A1: Photo showing shape of coil



SECTION A-A

FIGURE A2 - 20-TURN WINDING DIMENSION LIMITS

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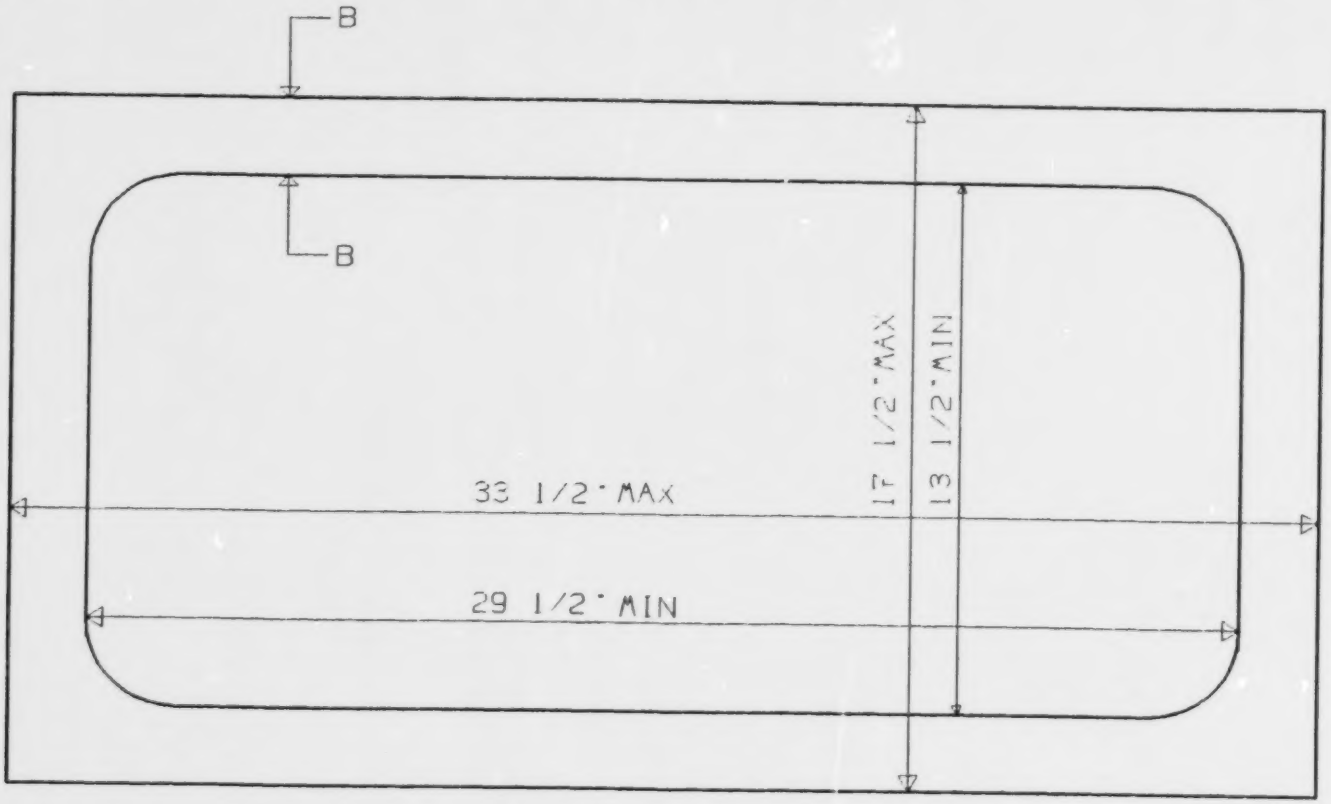


1 1/2" MAX

2" MAX

DOTTED LINE SHOWS WINDING DIMENSIONAL LIMITS

SECTION B-B

NOTE: FRAMING ATTACHMENTS MAY LIE OUTSIDE OF THE ABOVE DIMENSIONAL LIMITS SUBJECT TO CONSTRAINTS OF FIGURE 4

FIGURE A3 - WINDING FRAME DIMENSION LIMITS

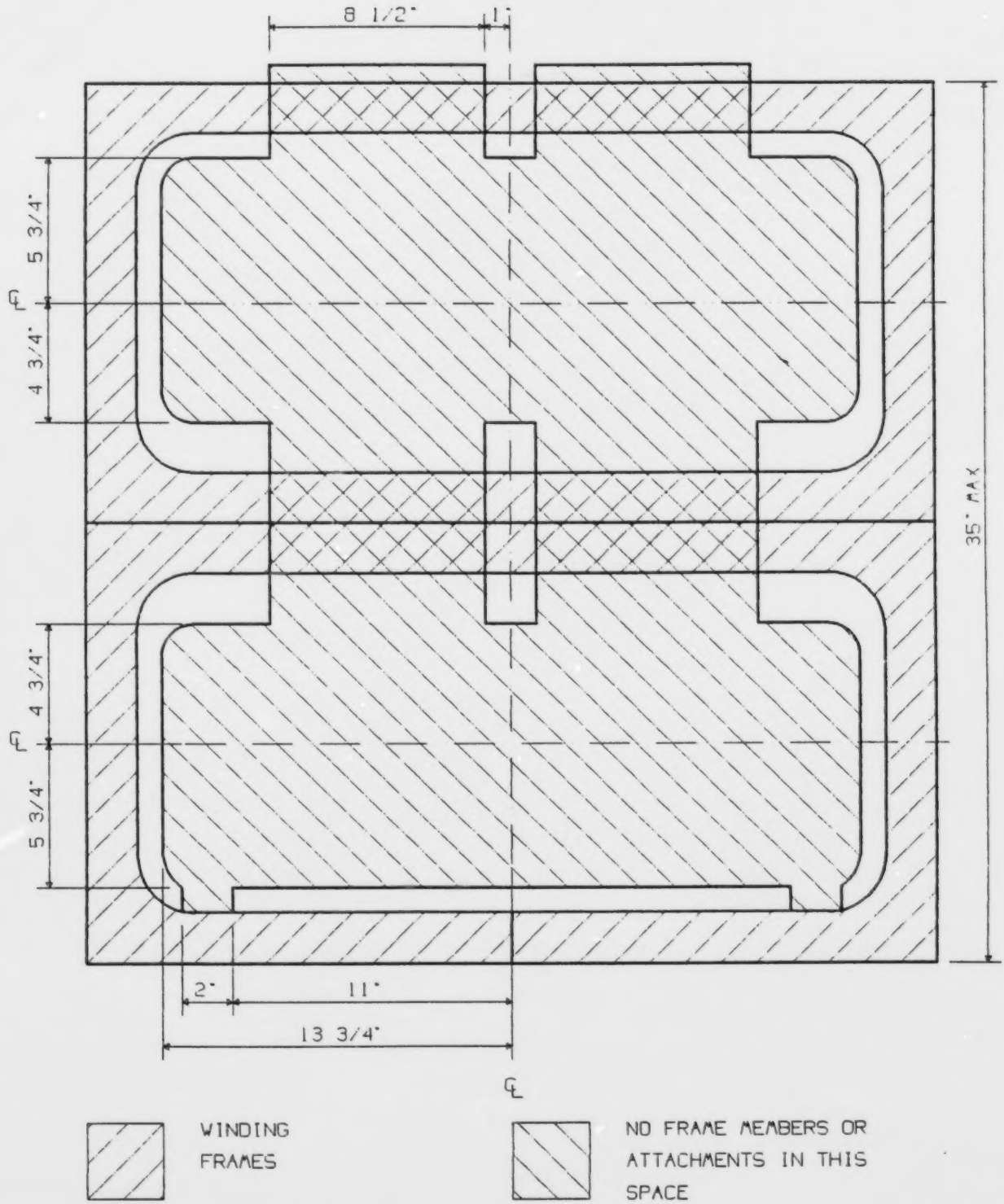


FIGURE A4(A) - ASSEMBLED COIL DIMENSIONS (ELEVATION)

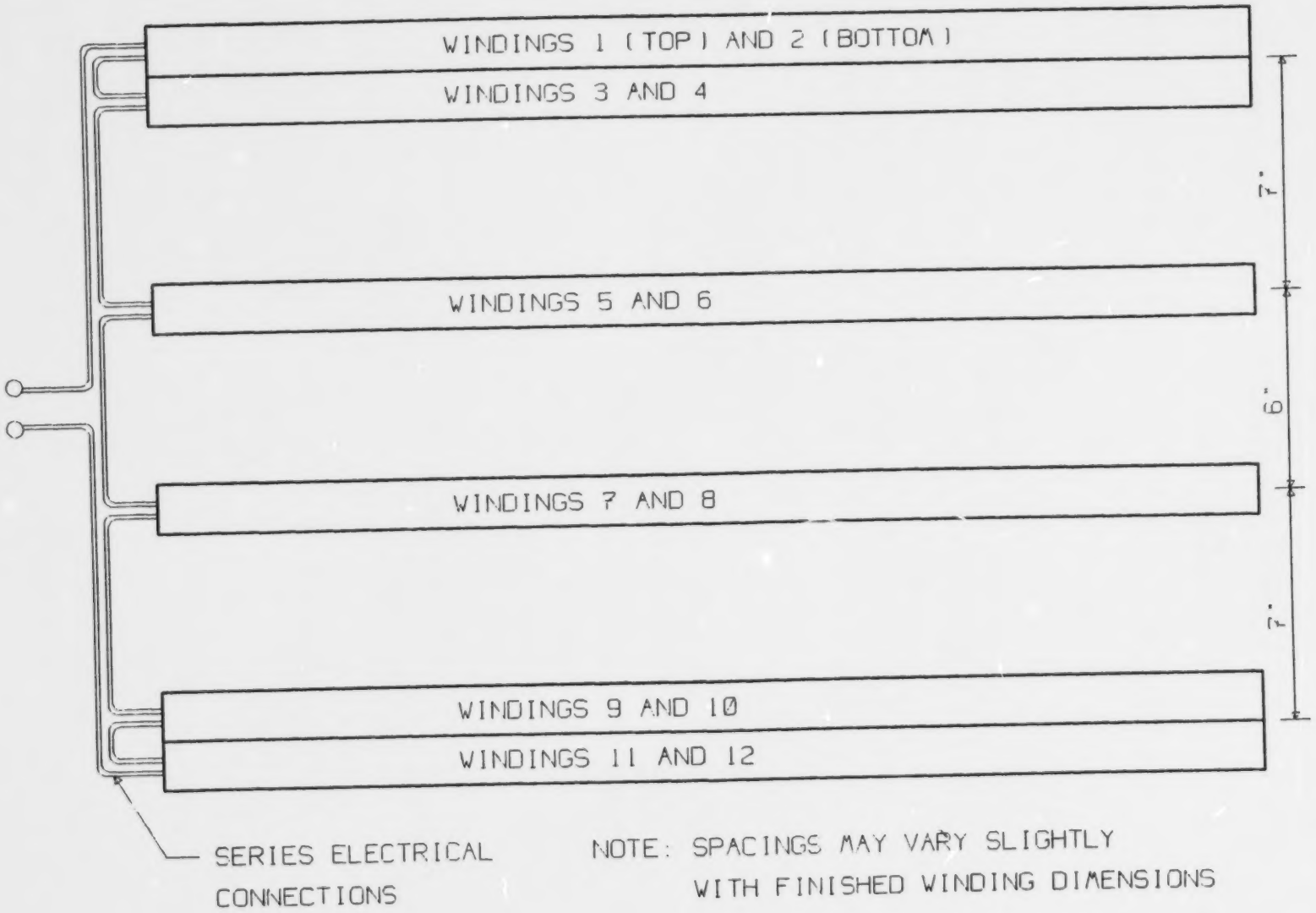


FIGURE A4(B) - ASSEMBLED COIL DIMENSIONS (PLAN VIEW)

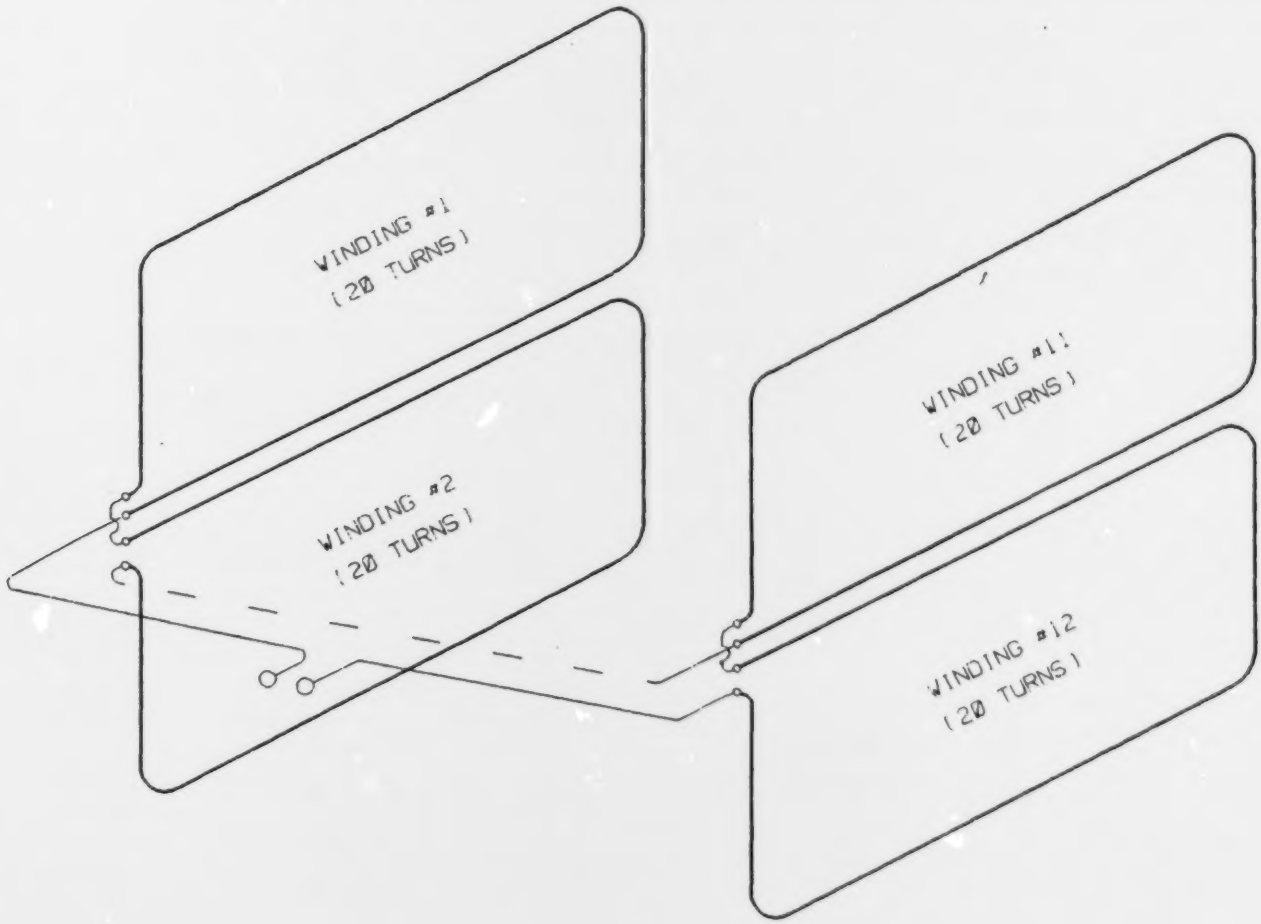
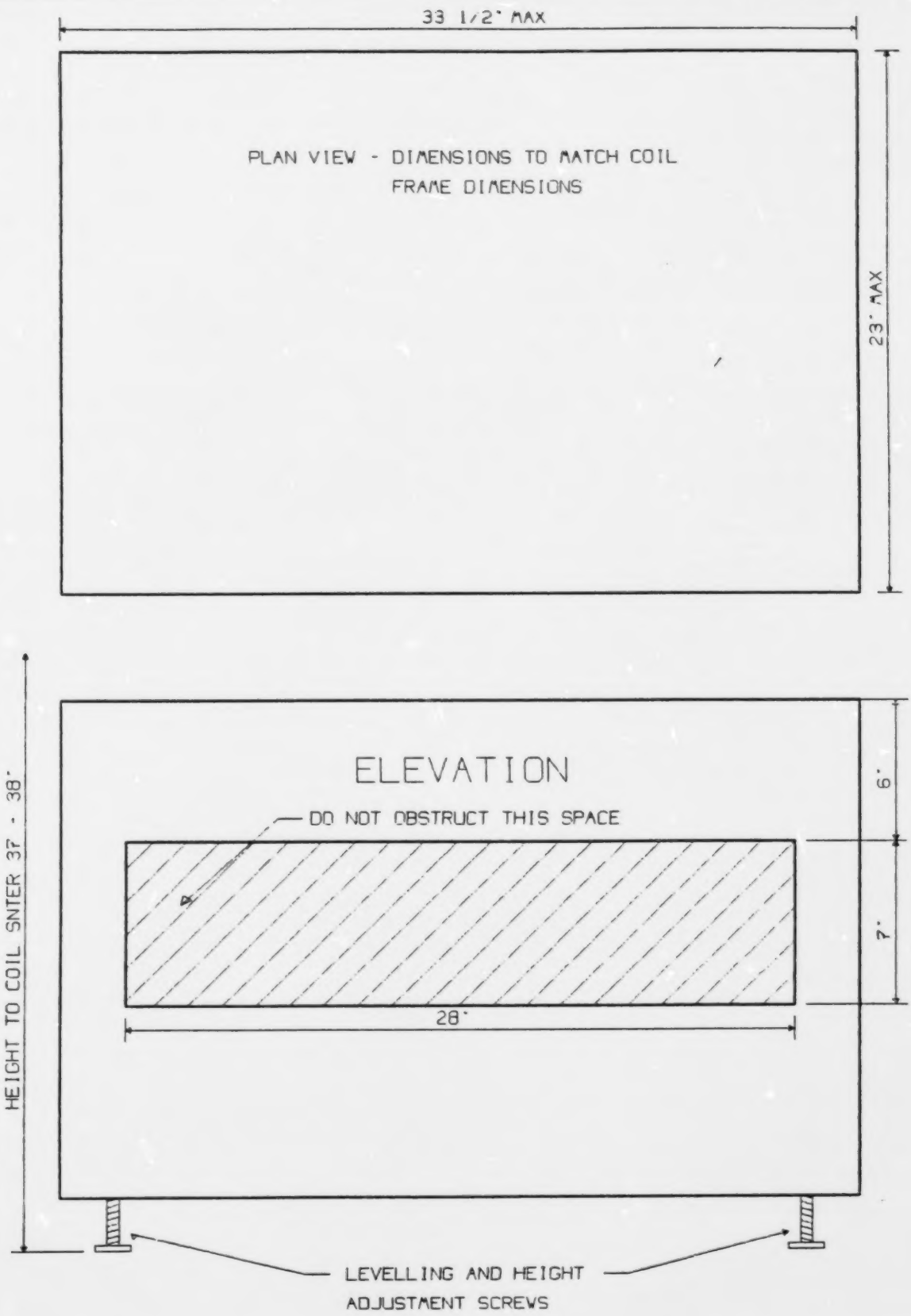


FIGURE A5 - SERIES WINDING CONNECTION. FOR SIMPLICITY, ONLY OUTERMOST WINDINGS ARE SHOWN



FIGUREA6 - SUPPORT STRUCTURE DIMENSIONS